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14. ABSTRACT Liquid monopropellant microthrusters utilizing electrolytic ignition were designed, fabricated, and analyzed. Low temperature co-fired ceramic tape technologies were used initially to fabricate microscale burners in order to evaluate the applicability of the technology to high temperature combustion systems. Microscale diffusion flames were stabilized in the burners, and optical spectroscopy measurements were performed to characterize the flame behavior. The low temperature co-fired ceramic tape technologies were then applied to the fabrication of microthrusters. The microthrusters had integrated silver electrodes to enable ignition of hydroxylammonium nitrate based liquid monopropellants by electrolytic decomposition. The volume of the thruster combustion chamber was 0.82 mm ³ . The microthruster was successfully ignited, and a thrust output of approximately 200 mN was measured with a voltage input of 45 V. Energy input as small as 1.9 J was achieved for ignition, and ignition delay as short as 224.5 ms was recorded.					
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INTRODUCTION

The development of microscale thrusters has recently drawn extensive research interest due to their potential applications on microspacecraft for primary propulsion and attitude control.¹ These research efforts are facing challenging obstacles such as the unavailability of proven microfabrication technologies for microscale chemical propulsion systems. Also, ignition becomes a problem in microthrusters due to the excessive heat loss in miniaturized systems. We address these issues in this paper by reporting on the fabrication and preliminary testing of a microscale liquid monopropellant thruster using newly developed low temperature co-fired ceramic (LTCC) tape technology which is capable of integrating metal electrodes inside the thruster during the fabrication process.

Although the concept of electrolytic ignition was first pursued in the 70s, relatively few studies on the technique have been documented. Risha et al.² recently investigated the electrolytic characteristics of a hydroxylammonium nitrate (HAN, $\text{NH}_3\text{OH}^+\text{NO}_3^-$) based liquid propellant, XM46, using a microfin electrode array. They demonstrated successful gasification and ignition of the liquid propellant using this concept. The concept has also been applied to other HAN-based monopropellants, such as RK315A and HAN/methanol/water mixtures.³ However, the integration of the ignition concept into a microthruster has yet to be pursued.

Several previous studies have utilized microfabrication technologies adapted from microelectromechanics (MEMS) systems.⁴⁻⁶ However, the complexity of silicon based MEMS techniques and the material properties of silicon have made further development of silicon based microthrusters very difficult. Ceramics, on the other hand, is an attractive material for developing micro and meso scale chemical thrusters. Alumina (Al_2O_3) based ceramics, such as mullite (60% Al_2O_3 and 40% SiO_2), feature good high-temperature strength, good thermal shock resistance, excellent thermal stability, and resistance to chemical attack by many compounds, making them excellent materials for high temperature microsystems such as chemical microthrusters.

Unfortunately, there exist few micro fabrication techniques that can construct alumina parts at sub-millimeter scales. Yetter *et al.*⁷ built an alumina micro thruster using ceramic stereolithography and demonstrated hydrogen/air combustion at a chamber pressure of approximately 8 atm⁸. Miesse *et al.*⁹ studied the flame dynamics of gas combustion in a mesoscale alumina burner with a semi-counterflow configuration. Their burners were constructed by machining Y-shaped slots on two polycrystalline alumina slides and then annealing them together. Fuel and oxidizer were introduced separately from the two legs of an inversed Y channel. Although the channel depth was small (0.75 mm), the lateral dimension of 5 mm was relatively large. Flame cells were observed in the microburners.

The low temperature co-fired ceramic (LTCC) tape technologies originally developed for packaging microelectronic devices were recently found to be useful for fabricating micro fluidic devices.^{10, 11} The low temperature ceramic consists of a mixture of alumina, glass, and binders; as a result, the maximum operating temperature is around 1200 K, which is considerably lower than pure alumina, but the serviceable temperature of LTCC is manageable for some combustor designs and operating conditions. Recent studies have shown the feasibility of using LTCC to fabricate catalytic microcombustors¹² and propulsion systems¹³; however, no gaseous homogeneous combustion in a LTCC microcombustor has yet been successfully demonstrated. Zhang *et al.*¹⁴ have also demonstrated the feasibility of developing solid propellant microthrusters using LTCC technologies.

In this report, our research on the fabrication of sub-millimeter scale counter flow diffusion flame burners to verify the feasibility of utilizing low temperature ceramic tape technology for high temperature reactors is summarized.¹⁵ From the experience gained on the fabrication and operability of these burners, we further applied the methodologies to the development of liquid monopropellant microthrusters with electrolytic ignition using LTCC tapes. Visual and high speed imaging of the thruster in operation are reported. Preliminary measurements of the thrust developed by the microthrusters are also reported.

FABRICATION AND CHARACTERIZATION OF A LTTC MICRO BURNER

Being able to fabricate micro burners using LTCC tapes may potentially help the realization of micro combustion systems (e.g., micro propulsion, micro power generation, fuel reforming, and in situ toxic waste incineration) due to the possibility of integrating electronic, optical, thermal, and fluid components into one microscale package. Towards this end, we have been fabricating LTCC micro stagnation-point flow burners to study the feasibility of using LTCC technologies to develop chemical microthrusters. Moreover, the burner was designed to allow investigations into the characteristics of laminar diffusion flames at sub-millimeter scales. The study also provides insight into the effects of length scale on flame stabilization and stretch with coupled heat loss, thus providing data and guidelines for designs of future microcombustors.

In the LTCC microburner, diffusion flames were established by two opposing jets of fuel and oxidizer ejecting from the internal channels on the side walls of the reaction channel. Sapphire windows on the top and bottom of the channel provided optical accessibility as well as gas seals. Three dimensional numerical simulations were implemented to evaluate the burner design as well as to compare model predictions with experimental results. The micro diffusion flame structures were experimentally investigated with a microscopic imaging spectrometer. The chemiluminescence characteristics of the flames, as well as their responses to changes in the flow field conditions, e.g., strain rates, were investigated.

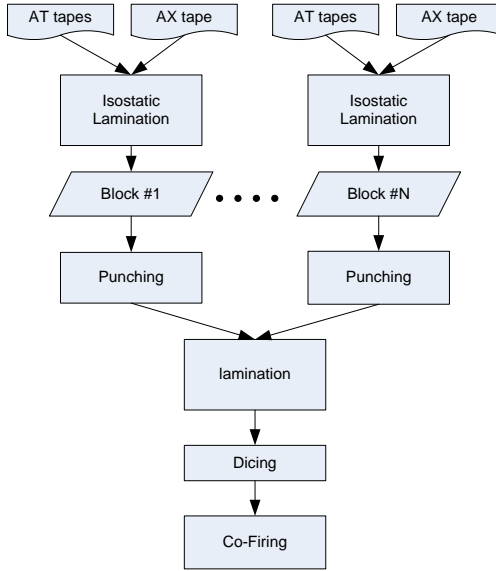


Figure 1: The fabrication process of micro chemical reactors using low temperature co-fired ceramic tape technologies.

The fabrication procedure of the LTCC burner started from laminating the blocks shown in Fig. 1. A combination of Dupont 951 AT and AX tapes, which have different thickness, was used to obtain the desired thickness of each block. The fired thickness of AT and AX tapes were $96.52\ \mu\text{m}$ and $215.9\ \mu\text{m}$, respectively. The blocks were laminated using an isostatic laminator which applied 3000 psi at $70\ ^\circ\text{C}$ to the stack for 10 min. The features were then cut out of each block with a punching machine. Honey was brushed on the interface between blocks before they were stacked together.

Pressurized lamination could not be utilized due to the existence of internal channels and cavities, but the whole burner stack was placed in a plastic bag and a vacuum was pulled on the bag to ensure that the honey was uniformly distributed over the interfaces. The sapphire windows were co-fired with the LTCC tapes, so they were inserted during stacking of the LTCC blocks. The burner stack was then retrieved from the plastic bag and diced (4 burners on a tape stack) using a dicing chopper.

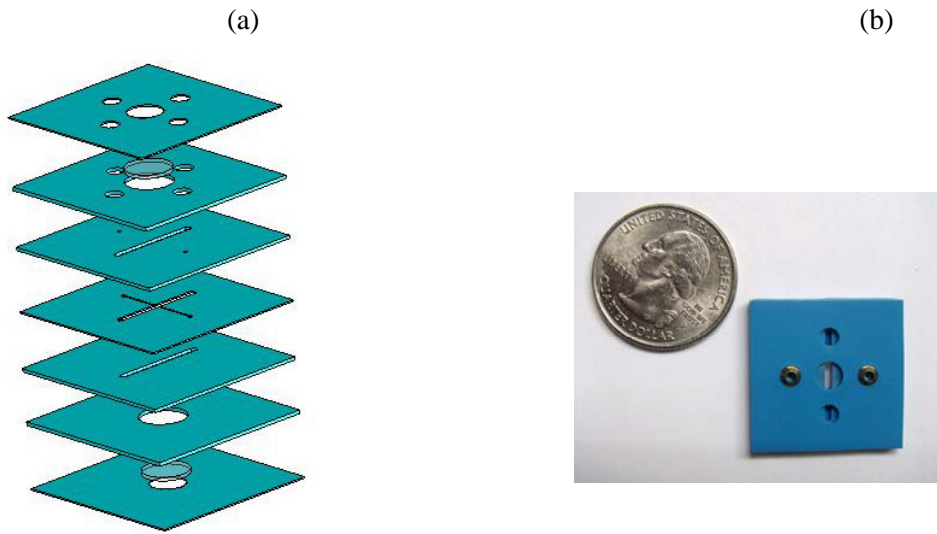


Figure 2: (a) The design of the LTCC burner, and (b) the LTCC burner after co-firing.

The design of the micro counterflow diffusion flame burner is shown in Fig. 2(a). Internal channels can be easily integrated into the burner design using the LTCC tape technologies. The burner consists of seven prelaminated layers and two sapphire windows which were cofired with the LTCC layers. The size of the injection ports was $221\ \mu\text{m}$ wide and $216\ \text{mm}$ in height. The cross section of the impingement region was $1.2\ \text{mm}$ by $1.2\ \text{mm}$. The length of the impingement region was 5 times the hydraulic length of the injection ports.

The reaction zone was confined by sapphire windows on the top and bottom surfaces, whereas the side walls were made of the LTCC material. The total length of the confined reaction channel was $12.7\ \text{mm}$ ($6.35\ \text{mm}$ on each side of the impingement plane). The LTCC counterflow diffusion flame burner after the co-firing procedure is shown Fig. 2(b). The overall size of the combustor was $25.4\ \text{mm}$ square and $3.3\ \text{mm}$ thick, similar to the size of a US quarter coin also shown in the figure.

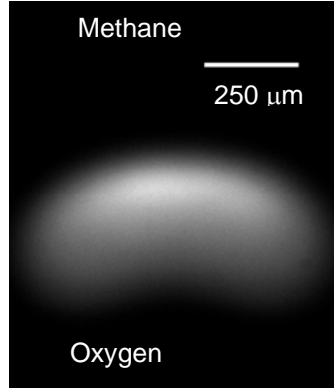


Figure 3: Experimentally observed luminous zone of the sub-millimeter scale methane/oxygen diffusion flame stabilized in the reaction channel of the LTCC burner.

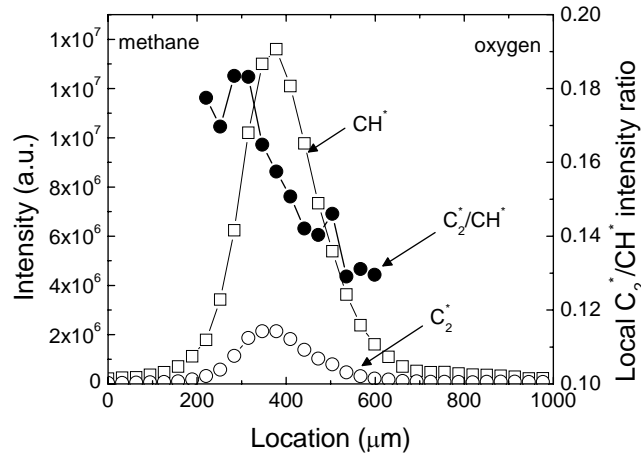


Figure 4: The distribution of CH^* and C_2^* chemiluminescence intensities of the methane/oxygen flame along the central injection port axis across the reaction channel in the counterflow diffusion flame burner.

Figure 3 shows the experimental line-of-sight observation of the flame. The picture was taken with a cooled CCD (TSI 14-10) through an inverted microscope (Nikon, TE-2000U). The flame width was approximately $250\ \mu\text{m}$ and 1 mm long. The volumetric flow rates of methane and oxygen were 4.55 and 9.28 sccm, respectively.

Figure 4 shows the distribution of CH^* and C_2^* intensities and the corresponding local C_2^*/CH^* ratios across the flame. The methane and oxygen flow rates were 13.8 and 22.8 sccm, respectively. The profile was obtained using a microscopic imaging spectrometer, which was able to provide one-dimensional spatial spectrograms. C_2^* intensities were quantified by integrating the intensities measured between 514.5 and 517.5 nm on the spectrograph capturing the (0,0) transition at 516.5 nm of the Swan band chemiluminescence. CH^* emission intensity was quantified utilizing emission between 426 and 436 nm, which corresponded to the Q-branch of $\text{CH}^* \text{ A}^2\Delta\text{-X}^2\Pi$ (0,0) transition. The full-width-half maximum (FWHM) of the CH^* profile is slightly larger than that for C_2^* , and the peak intensity of C_2^* luminescence falls towards the fuel side compared to that for CH^* . Also, a quasi-linear declining trend of C_2^*/CH^* ratio toward the oxygen side was found across the luminous flame zone.

DESIGN AND FABRICATION OF THE ELECTROLYTIC MICROTHRUSTER

The design of the electrolytic microthruster consisted of three layers as shown in Fig. 5. The electrodes on the inner surfaces of layer 1 and layer 3 provide direct contacts for electrolytic reaction of the HAN based liquid monopropellant to occur in the thruster combustion chamber. The thruster combustion chamber and nozzle were fabricated on layer 2 using micro punches. Vias were punched on layers 2 and 3 and filled with conductor paste. The vias and wiring patterns on layer 1 and layer 3 provides electric connections between the electrodes and the electric contacts on the outer surface of layer 3.

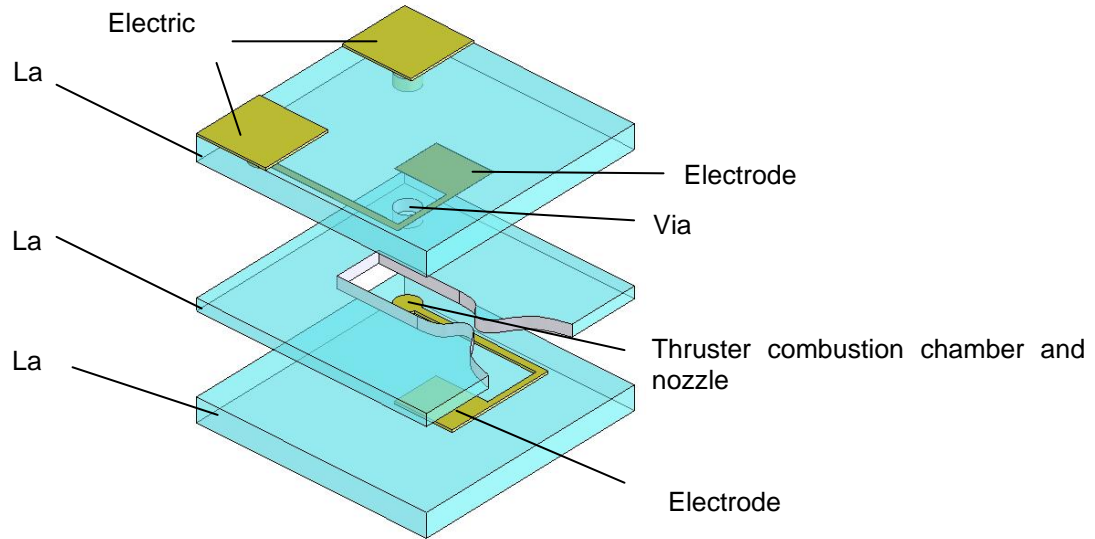


Figure 5: Exploded view of the LTCC electrolytic microthruster design.

Similar to the manufacturing of the LTCC burner (see Fig. 1), LTCC tapes were prelaminated with an isostatic laminator at 70 °C and 3000 psi to obtain the required thickness of each layer in the design. Four AT tapes were laminated for layer 1 and 3, and layer 2 consisted of three AT tapes. The thickness for layer 1 and 3 are therefore approximately 386 μm after cofiring, while the thrust chamber is 290 μm thick. Patterns of the thrust chamber and the nozzle, vias, and alignment holes were punched using a micro punch system. After the electrode and wiring patterns were screen printed on layer 1 and 3 with silver cofireable ink (Dupont 6141), they were dried in a 60 °C oven for 15 min. The three layers were then laminated with an organic fluid (85 % honey (contains primarily fructose and glucose), 15 % distilled water)¹⁶ and pressed together at 70 °C and 3000 psi for 5 min. Since four thrusters were designed on each 3" by 5" LTCC tape stack, individual thrusters were cut out before being sintered in the oven. During the firing process, the oven temperature was ramped slowly to 500 °C at a rate of 1.5 °C/min from room temperature and held for 1 hour before being ramped up again to the sintering temperature of 850 °C

at a rate of 5 °C/min. The oven was kept at 850 °C for 30 min and then naturally cooled to room temperature.

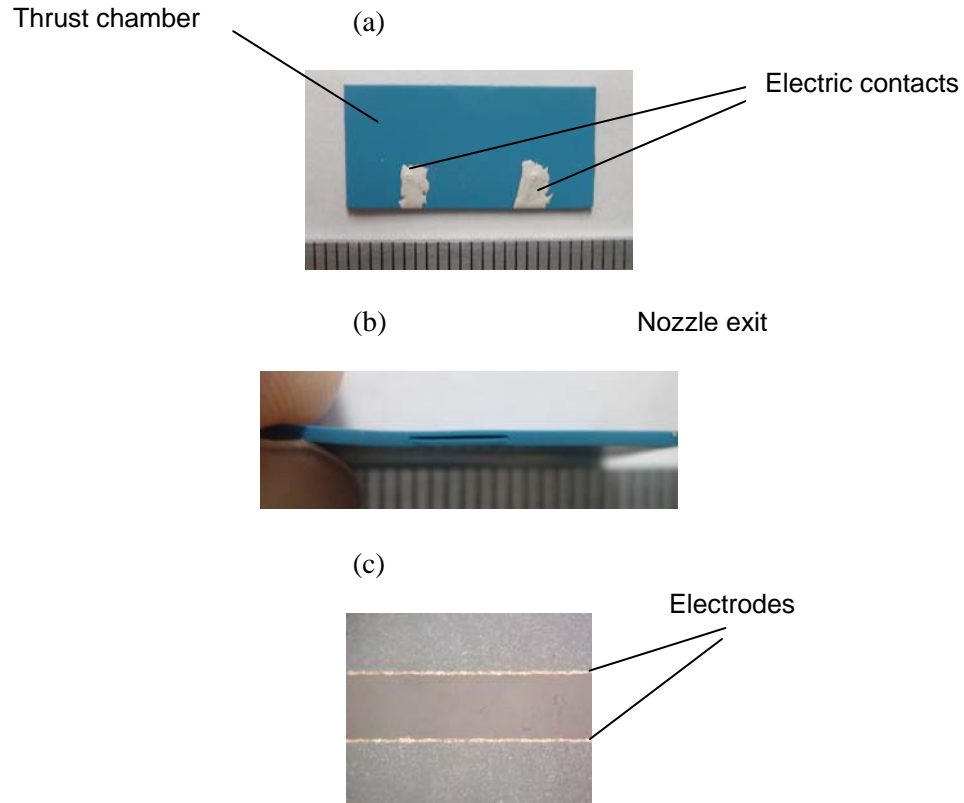


Figure 6: (a) Top view of the microthruster, (b) The close-up view of the nozzle, and (c) microscopic view of the cross section of the thrust chamber.

Figures 6(a) and (b) show top and side views of the microthruster, respectively. Dimensions of the whole thruster chip are approximately 25.4 mm wide, 12.7 mm in height, and 1 mm thick. The volume of the internal combustion chamber is 0.82 mm^3 . The silver electrodes cover the entire top and bottom surfaces of the chamber. The half angle of the nozzle contraction is 54° and 15° for the nozzle expansion. Figure 6(c) is a microscopic view of the cross section along the symmetric line of the

microthruster. The silver electrodes which are approximately 10 μm thick can be clearly seen to be uniformly printed on the opposing surfaces of the combustion chamber.

OPERATION OF THE ELECTROLYTIC MICROTHRUSTER

Figure 7 shows the experimental setup for studying the operation of the LTCC electrolytic microthruster. A dc power supply provided the current flow for the electrolytic process. The power supply (Agilent 6674A) was in constant voltage mode with a clipping current of 30 A. The output voltages as well as the output currents from the power supply were recorded using a data acquisition system (Nicolet LDS Genesis).

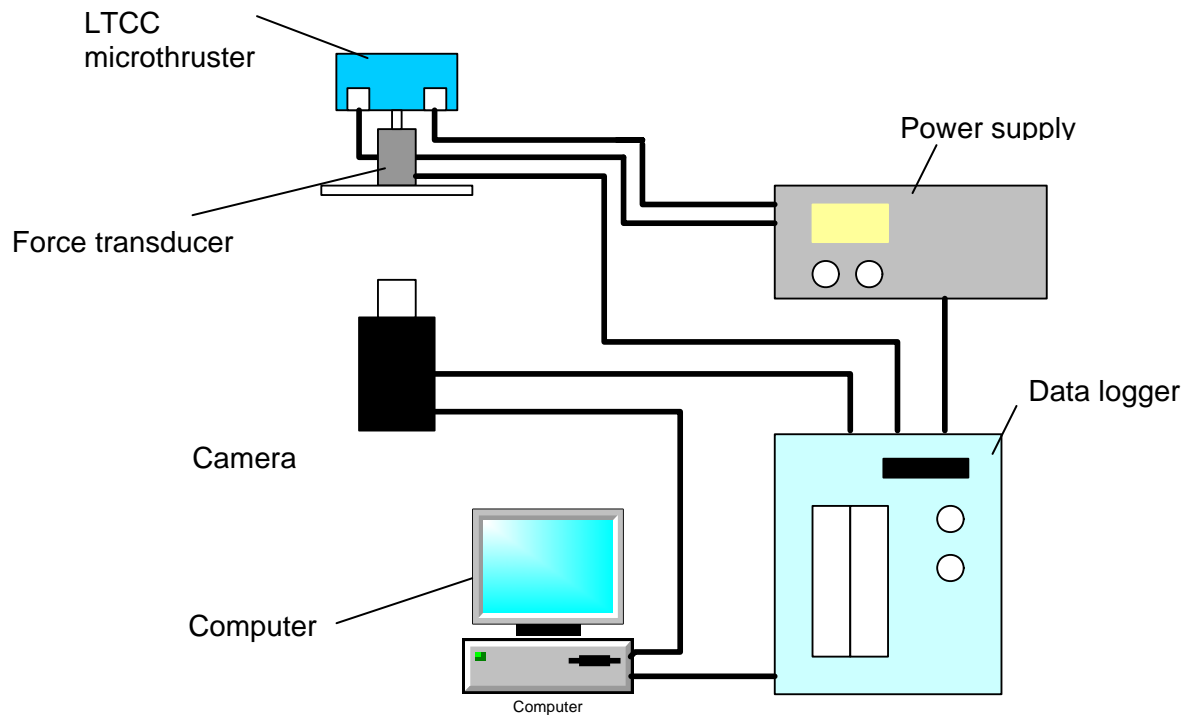


Figure 7: The test rig for the LTCC electrolytic microthruster.

The rising edge of the voltage output from the power supply was used to trigger a high speed camera (Vision Research, Phantom v7.3) which recorded the entire firing process of the HAN based liquid monopropellant in the microthruster. During thrust measurements, the microthruster was mounted vertically on a micro force transducer (PCI, U209C11) with a resolution of 0.0001 N.



Figure 8: The plume at the moment of full ignition of the microthruster.

During the operation, HAN based liquid monopropellant (RK315A) was filled manually into the thrust chamber using a hypodermic needle (Small Parts, GA-35, O.D. 147 μm , I.D. 63.5 μm) attached to a syringe. After the thruster was filled with liquid propellant, it was mounted on a stand and a voltage was applied across the electric contacts on the thruster. A current loop was built as the ionic flow in the HAN based liquid monopropellant was initiated. The proton transfer reaction is considered to be exothermic. The heat release further enhances the thermal decomposition of the liquid propellant. In the meanwhile,

the gasification of the liquid propellant through the electrolytic reaction increases the pressure in the thrust chamber which also expedites the ignition process. Figure 8 shows the plume when the microthruster is fully ignited. The picture was extracted from a movie captured using a regular DV video recorder (Sony DCR-SR100).

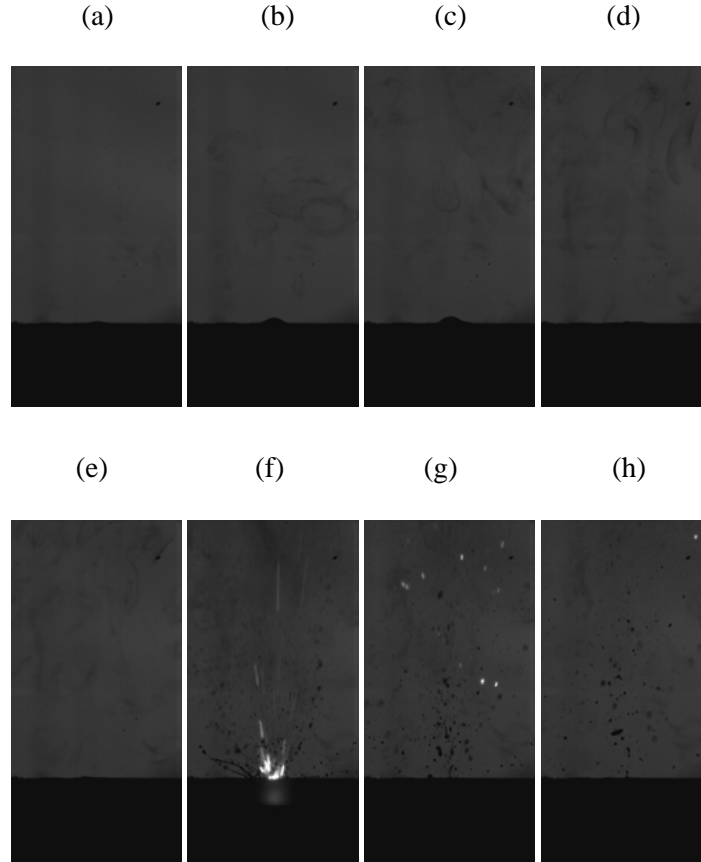


Figure 9: The electrolytic ignition process of the liquid monopropellant microthruster captured with a high speed camera at (a) 50, (b) 100, (c) 150, (d) 200, (e) 224 (f) 224.5, (g) 225, (h) 225.5 ms after the ignition voltage was applied.

Figure 9 shows the ignition sequence of the electrolytic microthruster. The voltage applied for the test shown is 45 V. An ignition delay of 224 ms was observed for the test. The process begins with gasification of the liquid propellant through the ionic reactions. The gas bubbles formed internally

pressurized the liquid propellant such that the liquid in the nozzle expansion section not covered by the electrodes were propelled and formed a liquid minuscule on top of the nozzle exit (see Figs. (a)-(c)). Liquid droplets being propelled out of the microthruster were also observed. Part of the gas bubbles could break through the liquid and were seen as smoke on top of the microthruster. Figure 9(f) shows the bright emission observed during the full ignition and combustion of the propellant in the microthruster. The bright burst was less than 1 ms, and also generated a audible pop noise. The thrust chamber became luminous as seen through the LTCC tapes during the burst indicating that the temperature at this stage might be high.

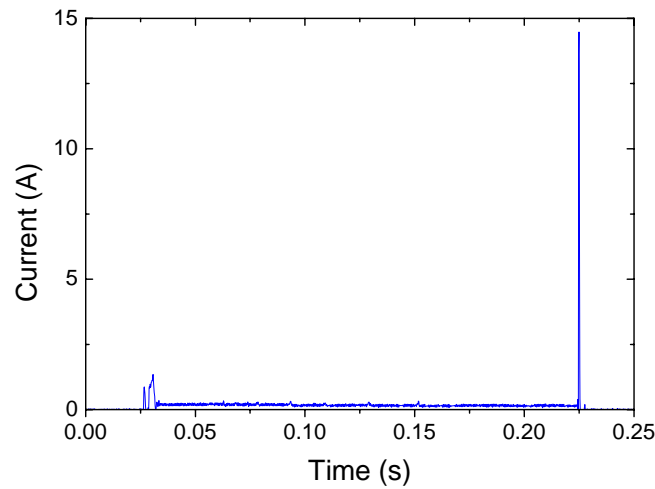


Figure 10: The evolution of the current flow during the ignition process.

The evolution of the current output corresponding to the case shown in Fig. 9 is plotted in Fig. 10. A current spike of 14.5 A was recorded exactly at the moment when the burst shown in Fig. 9(f) occurred. The current flow was not built immediately after the voltage was switched on but a lag of approximately 25 ms was observed. The delay is likely to be the induction time for the initial ionic reaction. As the ionic

flow was created, the overall current flow in the circuit increases up to approximately 1 A initially, but rapidly decreased to a stable current level of approximately 0.2 A.

The phenomena could be explained by the less efficient diffusive transport resulting from the reduction of effective contact area of the electrodes to the liquid propellant as gas bubbles were generated and covered the metal surfaces. The current became zero after the spike at full ignition even though a constant voltage output of 45 V was still maintained at the power supply indicating that all propellant was either consumed or propelled out of the thrust chamber. The total energy output of the power supply during the ignition process is estimated to be 1.9 J for the case shown in Fig. 10.

Figure 11 shows the thrust and current profiles during the ignition burst. The voltage applied was 45 V and a longer ignition delay of ~ 2.255 sec was recorded. The clipping of the output current indicates that the reactivity of the propellant becomes so high that the resistivity through ionic flow in the liquid propellant becomes negligible. The impedance across the liquid propellant becomes so small that the circuit draws all the maximum current the power supply is able to provide (50 A).

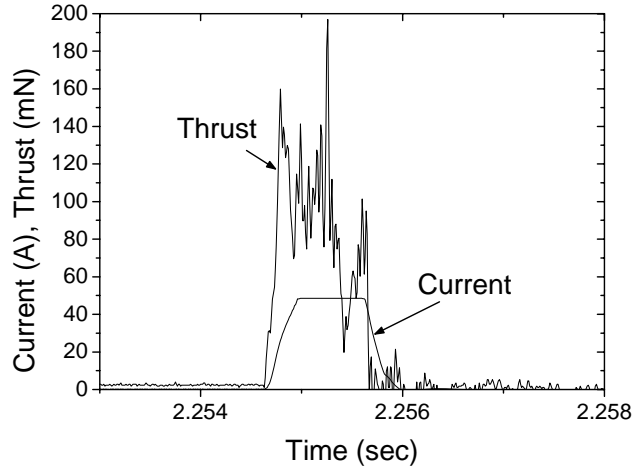


Figure 11: The evolution of the measured force and the corresponding current readings during the ignition burst.

The thrust measurement shows a maximum thrust of 197 mN for the currently designed HAN-based liquid monopropellant microthruster. The impulse is 3.1×10^{-3} N·s. The energy input during the ignition process for the case shown in Fig. 11 is 14.7 J. The reason for the large discrepancies on ignition delay and energy obtained for different tests under the same input voltage is still unclear.

CONCLUSION

In this study, we have shown the feasibility of fabricating a chemical micro burner and microthruster using the low temperature co-fired ceramic tape technology. Optical imaging spectroscopy was successfully applied to reveal the C_2^* and CH^* profiles across the microscale diffusion flame in the counterflow burner. Moreover, the electrolytic ignition concept has been proven to be applicable to achieve ignition in the microthrusters. The peak thrust output of the single shot liquid propellant microthruster was found to be 197 mN, and the total impulse is 3.1 mN·s. The duration of the impulse bit

is less than 1 ms. Ignition delay could be as short as 224.5 ms, and the minimum ignition energy required was 1.9 J.

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Combustion in Meso-scale Vortex Chambers (with M-H. Wu, Y. Wang, and V. Yang), Proceedings of the Combustion Institute, 31, 3235-3242, 2006.

Flame Acceleration and the Transition to Detonation of Stoichiometric Ethylene/Oxygen in Microscale Tubes (with M-H. Wu, M.P. Burke, and S.F. Son) Proceedings of the Combustion Institute, 31, 2429-2436, 2006.

Fundamental Studies on Electrolytic Ignition of Advanced HAN-Based Liquid Propellants for Space Propulsion Systems (with G. A. Risha, V. Yang and D. A. Fedorczyk) 54th Joint Army-Navy-NASA-Air Force (JANNAF) Propulsion Meeting (JPM) / 5th Modeling & Simulation Subcommittee (MSS) / 3rd Liquid Propulsion Subcommittee (LPS) / 2nd Spacecraft Propulsion Subcommittee (SPS) Joint Meeting, May 14-17, 2007, Marriott Denver City Center, Denver, Colorado.

A LTCC Burner for Studying Micro Flames (with M.H. Wu and V. Yang) IMAPS/ACerS 3rd International Conference and Exhibition on Ceramic Interconnect and Ceramic Microsystems Technologies (CICMT), April 23-26, 2007, Grand Hyatt Hotel, 1750 Welton Street, Denver, Colorado USA.

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